Self-Sufficient Streetlights on the Lincoln Alexander Parkway

Group 173

Complex Report

2024-03-30

ENG 3PX3

Mohammed Sahooly

Haseeb Ayub

Dannick Butera

Alex Di Francesco

Contents

Change Log

Change No.	Type	Description	Original	New	Section	Page
1	Revision	Tables aren't separated by page.	Table was separated by page.	Tables now look more professional	Throughout	all
2	Addition	Included Excel Files for NPV	Not included	Excel File Included	n/a	n/a
3	Addition	Included Excel Files for Risk Management	Not included	Excel File Included	n/a	n/a
4	Addition	Stochastic Sensitivity Analysis Section Added	Not included	New Section Added	Stochastic Sensitivity Analysis	23

1. Problem Identification

In 2018, the Hamilton Municipal Government reported a total of 182 automobile collisions along the Lincoln M. Alexander Parkway (the Linc), 32% of which happened during nighttime hours [1]. As a team of engineers, we have noticed that the Linc has insufficient street lighting, which we believe to be a major contributor to the significant number of crashes occurring out of daylight hours. Lack of lighting provided on high-speed roads is dangerous for the residents of Hamilton and any commuter who uses the Linc in times of inclement weather or sub optimal lighting. While safety for drivers is the main concern for the Ontario Ministry of Transportation (MTO), it is important to consider both environmental and economic concerns as well. Typical solutions to this problem would be to construct additional standard streetlights, which are high cost and have no upside other than providing more light. We have devised a plan to implement more streetlights along the Linc while minimizing negative environmental strain and reducing costs by generating energy through integrated wind turbines. To simplify, in every light pole we plan to install along the Linc, there will be a helical wind turbine attached that will harness wind energy from both the environment and passing cars. When compared to traditional outdated streetlights, the government can save significant amounts of money from net zero energy costs to operate and also promote environmental concern by demonstrating care for the environment using new, green innovations. Constraints for this project include high costs/budgets, engineering constraints on the technology, and possible lack of existing electrical infrastructure. Residents will approve of tax money being spent to keep roads safer, and the environment cleaner, while the government can look at this project as a way to switch to permanent self-sustaining infrastructure. This report will also compare the construction, materials, time, maintenance, and design costs to determine the practicality of our proposed solution.

2. Detailed NVF and Conversion Factors

NV = - [# of light poles(construction materials + electrical materials)] - [# of light poles*(installation costs) + traffic closure cost] - [Design + Administrative Costs]*

+ [Value Benefit of Road Conditions] + [Value of Energy Generated – Energy Used] + [Cost Benefit of Clean Energy Promotion]

Fig. 1. Proposed Solution Detailed Theoretical Net-Value Function

Above, we have our detailed NVF, which contains each of the costs and benefits associated with our streetlight design. Each of the parameters has some conversion factor to yield a cost or benefit value in dollars or are a cost that does not necessarily need to be converted to dollars.

The parameters of the solution can be split into both costs and benefits. Analyzing the costs first, the first is the cost of the light poles themselves. This is calculated by multiplying the number of light poles by the materials cost and electrical hardware materials needed for each light pole, which includes the base, turbine and generator and bulbs, we assume that every light pole will be identical, yielding a total dollar amount. Next, the cost of installation is analyzed, where we again, assume that the installation process, procedure and cost will be identical for all 175 poles. The cost here includes the installation and also the cost of traffic closures during the installation. We also assume that based on the location of the poles, only a single lane will be closed on either side for the installation duration. Finally, we factor in the cost to design and administrate the turbine and associated processes, which we allow to be a fixed initial cost.

Finally, we analyze the benefits associated with the project, which again include monetary values so that they can be directly added to the costs to determine a net value. First, the value benefit of safer road conditions is considered, and is the main reason for this project. While difficult to quantify, the value is determined via a cost associated with safer conditions per driver, multiplied by the number of nighttime drivers. Next, we take the difference of the value of the energy generated from the energy used by the light pole, which for this case is placed in the benefits section of the NVF

as it is assumed to be positive. This energy in kW is then converted into a cost using the local cost of wind energy in Hamilton. The last parameter is also one that is less simple to quantify as it is the socioeconomic benefit of the widespread use of clean energy. This is quantified by assuming this project will reduce the need to spend money on resources that promote renewable energy, as the project acts that way.

Ethical considerations are arguably the most important part of this project and is the main motivation behind it's development. The lighting is being installed to promote safety, which is a difficult parameter to quantify monetarily but the value of safety is paramount and is the reason this project is being conducted.

Regulations followed pertain to both the design and the construction of the light poles. The regulations regarding the design, installation, operation and maintenance of street lights by

Ontario's Electrical Safety Authority will be followed closely, specifically sections 1.0 through 4.0.

3. Initial Solution Comparison

The proposed solution we have analyzed in this report is only one of the possible options the MTO and Hamilton government may consider. While implementing wind powered streetlights is a feasible solution, it is important to compare to traditional solutions such as using installing more basic streetlights such as the ones already along the Linc, or choosing to not alter the highway lighting conditions at all.

Option 1: Traditional Street Lights

If the government realizes the need to introduce more lighting along the Linc, we can generate a simple estimate of how much the project would cost in the form of a net-value function.

NV_1 = - *[# of light poles*(construction materials + electrical materials)] – [# of light poles*(installation costs) + traffic closure cost] – [Energy Used] + [Value Benefit of Road Conditions]*

NV_1 = - *[175*(945)] – [175*(1290) + 5000] – [220,500] + [365,000] =* ***-$251,625***

Fig. 2. Estimate Net-Value Function of Traditional Street Light Solution

Implementing traditional streetlights will decrease the initial costs of the project, as a typical light pole is cheaper, and installation time should be less. However, this typical solution lacks any additional benefits as it has no benefit to the environment or public. By estimating values for costs and benefits, this possible project has a value of about negative $250,000 over the next 10 years.

Option 2: No Changes

Although many drivers would prefer better lighting along highways, it is important to consider that the government may choose not to do any construction along the Linc. In this case the net-value function would be $0 and have no benefits or costs over the next 10 years. Reasons for no change could be due to a limit on government funding, lack of manpower, or political and societal concerns.

Proposed Solution:

Below is our teams net-value function for our proposed solution of introducing wind powered streetlights.

NV = - [# of light poles(construction materials + electrical materials)] - [# of light poles*(installation costs) + traffic closure cost] - [Design + Administrative Costs]*

+ [Value Benefit of Road Conditions] + [Value of Energy Generated – Energy Used] + [Cost Benefit of Clean Energy Promotion]

NV = - [175(406 + 690)] - [175*(1720) + 5000] - [25,000 + 5000]*

+ [365,000] + [2,529,450 – 220,500] + [60,000]

= -[527,800] + [2,733,950]

=$2,206,150

Fig. 3. Proposed Solution Detailed Net-Value Function with Full Calculation

To find warranted values/cost coefficients in our net-value function, we performed a technical analysis on all the major parameters to generate the most accurate estimate possible. Materials cost was calculated based on the amount of steel needed for each light pole, in addition to electrical components such as lightbulbs and the wind turbine itself. Pricing was sourced from suppliers where possible, and assumptions where pricing could not be found. Installation costs were calculated by assuming manpower costs for a team of 3, spending 8 hours per streetlight with the help of equipment and machinery. And additional lane closure/traffic control cost of $5000 was added. The design and administrative costs was assumed to cost no more than $30,000 combined. Energy generated and energy used was calculated by considering the wattage of lightbulbs and subtracting it from the cost that the proposed wind turbine would generate. This excess energy would be sold back to the grid, or re-allocated to other electrical components such as stoplights, causing a large net positive in energy costs. Both the value from better road conditions and clean energy promotion was calculated using very general assumptions, considering that it is hard to convert such to monetary value. Positive road conditions is calculated by taking an approximation of 10,000 daily nighttime drivers multiplied by a factor of 1 cent per driver as a safety benefit factor, which then was converted to an dollar amount over a 10-year period. Similarly, the clean energy promotion factor, which considers the benefit from taxpayers seeing innovations in green technology was decided upon by 20% of Hamilton's yearly energy promotion budget over a 10-year period.

4. Technical Analysis Overview & Detailed NVF

Haseeb Ayub: Value of Energy Generated:

$$\begin{aligned}\$\ of\ energy\ produced &= (175\ street\ lamps)(hours\ in\ 10\ years) * \left(\frac{\$}{kWh}\right) * (generator\ constant) * (internal\ generator\ winding\ flux)\\ &* (\#\ of\ copper\ windings\ in\ generator) * (angular\ turbine\ velocity) * (generator\ efficiency)\end{aligned}$$

$$\$2529450 = (175)(87600)(\frac{\$0.11}{hour}) * (0.4552) * (0.5) * (5500) * (1.865) * (0.65)$$

Range: Generator efficiency >=0, <= 1. Energy produced >0. Winding flux > 0. Generator constant >0. Windings >1. angular velocity > 0.

Fig. 4. Proposed Solution Energy Generation Calculation

Technical analysis was performed to quantify the dollar amount of energy generated by the turbine. The mechanical to electrical conversion is applied, and the resulting analysis is built on synchronous generator power generation. First is the generator constant, which utilizes the local air density and turbine geometry. Next, the internal winding flux of the generator is used, which is the assumed internal magnetic field strength. Next, the number of copper windings in the generator defines its size and power output, designed to produce roughly 1500 kW of energy. The angular velocity is then multiplied in and is a function of the turbine's geometry and average wind speed in Hamilton. Finally, it is multiplied by the generator efficiency, which is assumed to be significantly less than 1 and normalized by scaling the hourly generation to 10 years which can then be used in the NVF.

Mohammed Sahooly: Through a selected light type, maximize its efficiency and find the electricity cost while using wattage as a decision variable.

$$Cost\ of\ electricity\ = (kilowatts)(350\ LED\ lights)\left(\frac{12h}{day}\right)\left(\frac{0.11dollars}{kWh}\right)(365\ days)(10\ years)$$

$$Cost\ of\ electricity\ = (0.12kW)(350\ LED\ lights)\left(\frac{12h}{day}\right)\left(\frac{0.11dollars}{kWh}\right)(365\ days)(10\ years) = 202356$$

Fig. 5. Proposed Solution Cost of Energy Calculation

A technical analysis was conducted to determine the total amount of electricity consumed for running the streetlights for 10 years. Research was conducted to find the differences between certain light types, as given by another technical analysis, lumens of 40000 were required to cover the Linc on both sides of the road. We settled on two LED lights that can power both sides of the road. Nonetheless, to optimize efficiency, we used the following formula; Efficiency = 20000/Wattage, given LED streetlights the wattage ranges from 120-160, we can tell that 120 W would produce the most efficiency. W settled on the LEAF LED Streetlight which can produce 21000 lumens at 175 lm/w (efficiency). Such LED lights can be used to dim the lights when not needed at full brightness, creating a function with "kilowattage" which indicates the kilowatts that the light operates at, "$/kwh" indicates the average cost of electricity during the operating hours, and 12 hrs/day will be the hours of operation, while the other values calculate the total time (10 years). The decision variable is kilowatts, so we calculated that the maximum electricity cost (0.12kW) would be 202,356 CAD in 10 years for 175 streetlight poles and 350 Led Lights. While this cost value can range below the maximum if dimmed properly. Such an efficiency concept was taught in a civil engineering environmental class (2b03) with the topic of pollution through electricity consumption.

Alex Di Francesco: Pole thickness, Cost of steel.

To ensure the light pole could withstand the necessary wind speeds, I concluded the light pole would need to withstand 40 m/s windspeed. From the affected area, I found the pole would be subject to 1040 N/m^2 of pressure, equivalent to 416 N/m. Using knowledge from CIVENG 3G03, (structural analysis) I was able to find the max deflection of a cantilevered pole depending on the load, height, young's modulus, and moment of Inertia. The only unknown parameter in the equation was the moment of inertia. Inertia depends on the cross section of the cantilevered pole, which is proportional to its thickness. In order to solve for the thickness, I determined the maximum allowable deflection to be height of the pole divided by 360, which is the industry standard for similar situations. Solving for inertia, I determined the thickness of steel needed to have less than the allowable displacement. Using 4mm thickness, I converted the cost of steel/kg to cost/m of pole by multiplying the cost/kg by density in kg/m^3 by the average cross-sectional area to determine the cost of steel would be $40 per m of pole needed.

Dannick Butera: Streetlight Height and Interval Distance

Based on an understanding of optics obtained from CIVENG 2A03, we can determine the height and quantity of streetlights required to satisfy this project's needs. Within this course, it was explained that light propagates radially, which is a fundamental concept to help approximate the expected impact that a streetlight has on the road.

Assuming the streetlight acts as a point source of light, mathematical formulae can be used to determine its expected illuminance. Further computations (found in appendix) can also be used to determine the point source distance required to illuminate a certain surface area. As the light is propagated radially between westbound and eastbound traffic, its diameter must be at least 35m to adequately illuminate all four lanes and the shoulders of the highway. Thus, the area must be at least 962m^2.

We will use an illuminated area of 970m^2 to account for potential errors and external factors causing a decreased area over time. Assuming a 40000-lumen light to match existing innovative standards, the equations yield a required height of 10.15m.

The observed section of the Linc is currently 8.5km long, and 2.4km is already illuminated, resulting in 6.1km left to be illuminated. This converts to 175 streetlights that each illuminate circular projections of 35m diameters, each separated by 35 meters respectively. This directly affects our NVF by providing the quantity of streetlights required and thus their corresponding cost.

NV = - [# of light poles(construction materials + electrical materials)] - [# of light poles*(installation costs) + traffic closure cost] - [Design + Administrative Costs]*

+ [Value Benefit of Road Conditions] + [Value of Energy Generated – Energy Used] + [Cost Benefit of Clean Energy Promotion]

NV = - [175(406 + 690)] - [175*(1720) + 5000] - [25,000 + 5000]*

+ [365,000] + [2,529,450 – 220,500] + [60,000]

= -[527,800] + [2,733,950]

=**$2,206,150**

Fig. 6. Updated Net-Value Function as a result of decision variables

5. Sensitivity Analysis

After performing a sensitivity analysis on our proposed solution, it was made clear which parameters' variance would alter our net value the most. Two methods introduced in lecture were employed to detect sensitivity: the spider plot and the tornado plot (see page 10). The input parameters were those included within the technical analysis, in addition to another relevant parameter included in the net value function. These parameters are outlined and detailed below.

Streetlight Height

Streetlight height is functionally responsible for determining the surface area that each light will illuminate. It is also crucial to our material costs, as a taller pole requires more material. This parameter is measured using units of meters, and can range from 10.15m to 13m. As can be seen through the spider and tornado plots, our net value is moderately sensitive to changes in streetlight height. Another observation to be made is that they are inversely related, suggesting that increasing our height will decrease our net value. Going forward, we should look to ensure we have a middle ground where there is a sufficiently large surface area illuminated, while not decreasing our NV significantly.

Streetlight Interval Distance

Streetlight Interval Distance (SID) represents the distance between each streetlight added along the Lincoln M. Alexander Parkway. The unit for this variable is also meters, and its range of 35-65m was determined through calculations and real-world observations. This parameter is directly related to the number of streetlights our solution will require, as a larger interval would result in a lower number of streetlights and vice versa. This relationship is indirectly displayed in the spider plot, which demonstrates that an increase in SID yields a higher net value (as less streetlights will reduce costs). In addition to the net value being quite sensitive to changes in SID, it is with note that the relationship is not linear, instead the net value decreases exponentially as SID is reduced. This suggests we should strive to avoid a decrease in this parameter and consider increasing it.

Generator Efficiency

Generator Efficiency pertains to the efficacy at which our turbine system yields power. In the context of energy, efficiency values are unitless and range from 0-1. However, the assumption was made that a generator with efficiency below 0.3 cannot be considered and such 0-0.3 was removed from our varying range for this parameter. As the generator efficiency is compounded to each of the 175 turbines, it is of major impact on our NVF. It is also clear that we should look to maximizing this parameter as it has a strong positive relationship with net value. Efficiency maximization can be done through remodeling or investment in novel technology.

Bulb Efficiency

LED lights with 120 W were chosen for their efficiency and energy-saving capabilities. Dimming mechanisms allow for adjusting wattage, reducing electricity costs and improving margins. Dimming before sunrise and after sunset, as well as during rush hours, optimizes savings. Efficiency in this context is measured in units of lm/W and typically range from 120-175 lm/w for our required bulbs. This parameter significantly impacts electricity expenses and is one of the sensitive parameters as it dictates most of the operational costs, if optimized properly it can provide the city with substantial benefits.

Accident Reduction Factor

This parameter represents the expected reduction of car accidents on the Linc due to the new illumination. It is a unitless factor that ranges from 0-1, with 1 being the total elimination of accidents. As there are a myriad of reason accidents happen, this factor is limited between 0.05-0.45 and only considered for nighttime conditions. Despite this small range, our NV is most sensitive to this parameter. This is due to the large number of collisions annually, and the large cost of each collision. As this parameter is currently just an estimation, it is of supreme importance to develop further research to deduce its specific range or expected value.

Other Variables

In addition to the parameters, other parameters would influence the net value of our proposed solution. One of which is the cost (in $CAD) of renewable energy advertisement. The government is adamant about the importance of renewable energy and looking for ways to promote it, however, there is no concrete data to quantify the importance or impact of our solution on this market.

There are also discrete (non-continuous) parameters that could not be fit to a spider or tornado plot. Such parameters include pole material type and bulb type. However, as they are discrete, it was simpler to deduce the optimal selection without having to worry about tradeoffs or estimates.

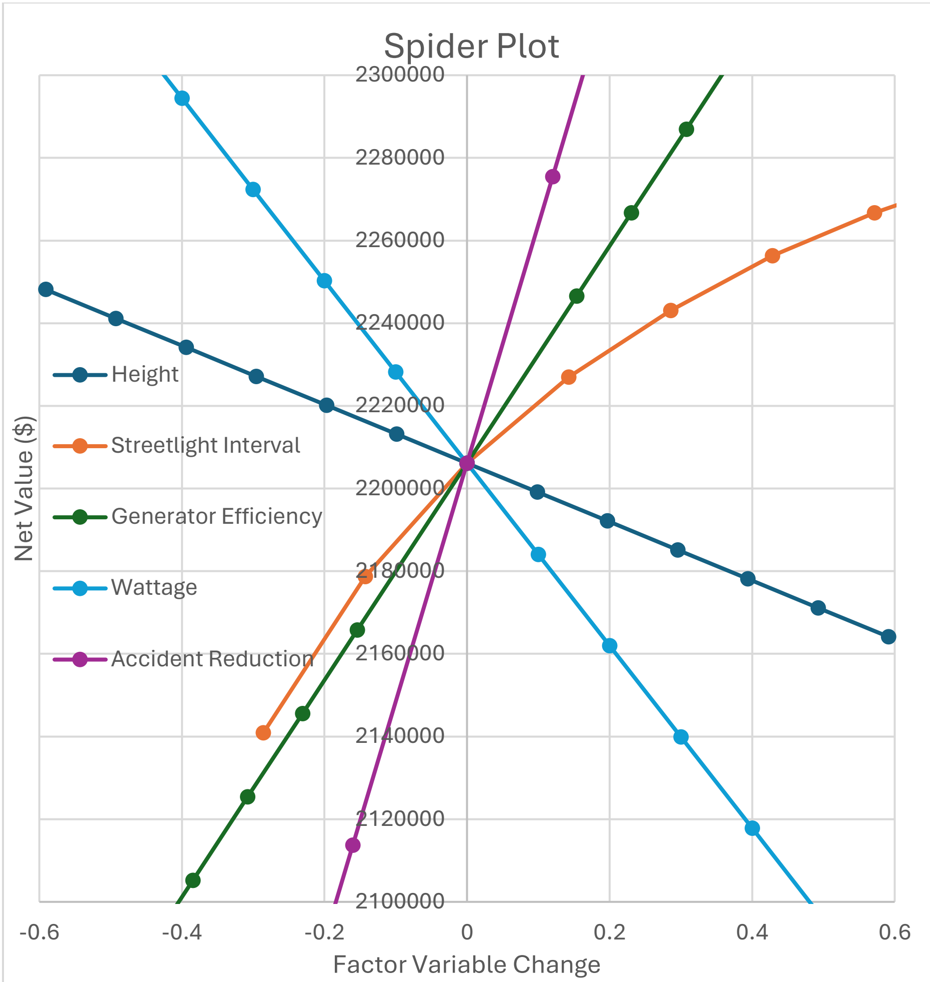


Fig. 6. Proposed Solution NVF Variable Comparison Spider Plot

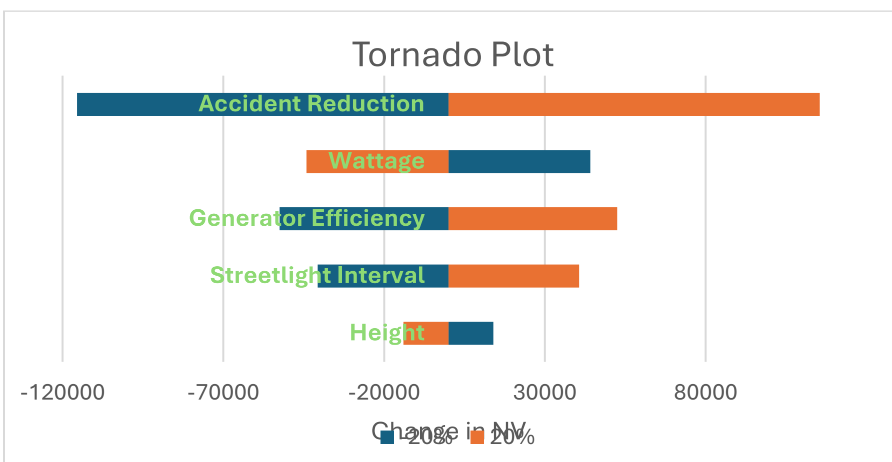


Fig. 7. Proposed Solution NVF Variable Comparison Tornado Plot

6. Optimization

The initial optimization of our decision variables was completed using Excel's built-in solver tools. The first two parameters (streetlight height, streetlight amount) were optimized using linear programming, specifically the Simplex method. This method was effective and employed due to the objective functions for these two parameters being linear. However, the final two (pole thickness, bulb efficiency) had to be solved using a GRG nonlinear algorithm. This is because the objective function for pole thickness was of the form $C*x^2$, and the function bulb efficiency was of the form C/x. Both of these functions are nonlinear and thus couldn't be solved using linear programming, but instead nonlinear programming.

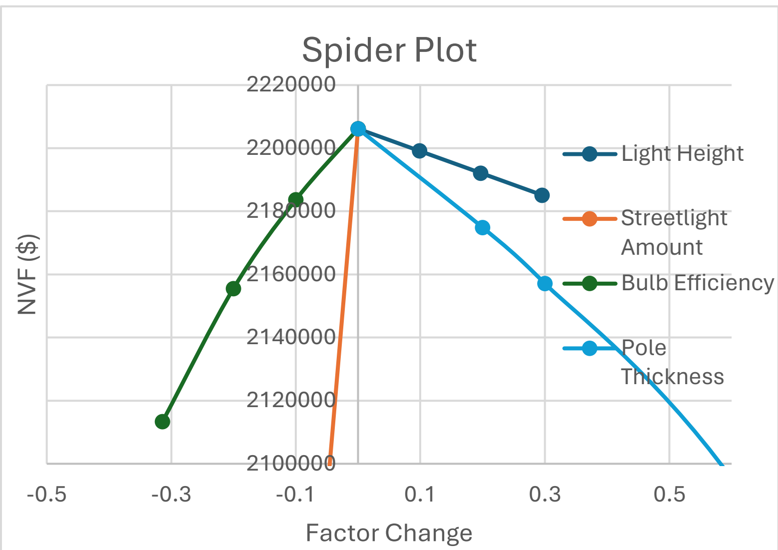


Fig. 8. Updated Spider Plot.

Variable Cells

Cell	Name	Final Value	Reduced Gradient
D4	Optimal Streetlight Height (m)	10.15	0
D13	Optimal Streetlight amount <=	175	0
D21	Streetlight Pole Thickness (m) <=	0.004	0
D29	Bulb Efficiency (lm/W) <=	175	0

Constraints

Cell	Name	Final Value	Lagrange Multiplier
C17	Constraints	175	0
C18	Constraints	175	-13357.99966
C25	Constraints	0.004	203000.1949
C26	Constraints	0.004	0
C33	Constraints	175	0
C34	Constraints	175	-1156.317664
C8	Constraints	10.15	7000.000212
C9	Constraints	10.15	0

Fig. 9. Optimization Sensitivity Report.

By observing the sensitivity report, certain findings can be reported. Every variable has a reduced gradient of 0 which suggests they cannot be further improved to help the solution. Lagrange multipliers with high magnitude suggest that increasing/decreasing a certain constraint would have a major impact on the optimal value. The constraint with the highest Lagrange value is the minimum thickness; this makes sense as thickness has a squared relationship with the NVF and thus would impact it strongly.

After the optimization, a thorough sensitivity analysis was performed on our NVF and the four decision variables. The control parameters were material cost, illuminated area, wind speed, and energy cost. NVF and variable values were computed for parameters undergoing increases and decreases of 10% to determine the sensitivity of each variable to every respective parameter.

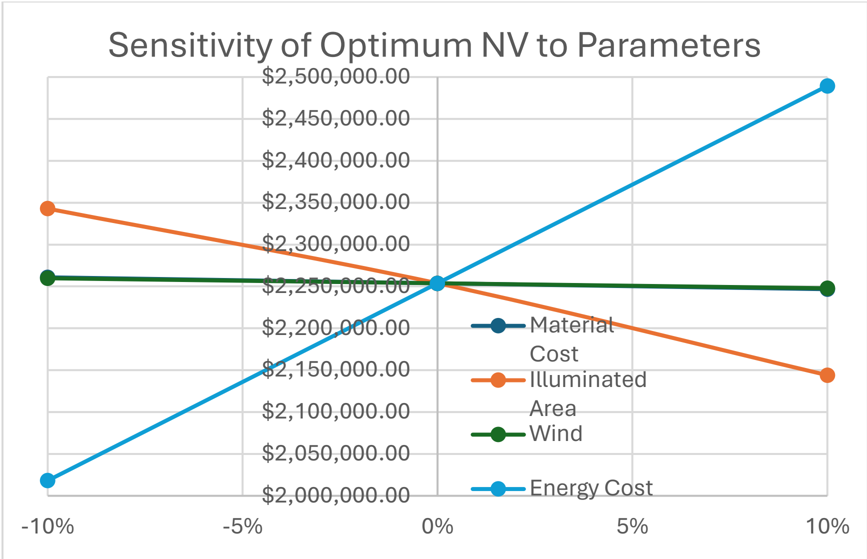


Fig 10. Sensitivity of Optimum NV to Parameters

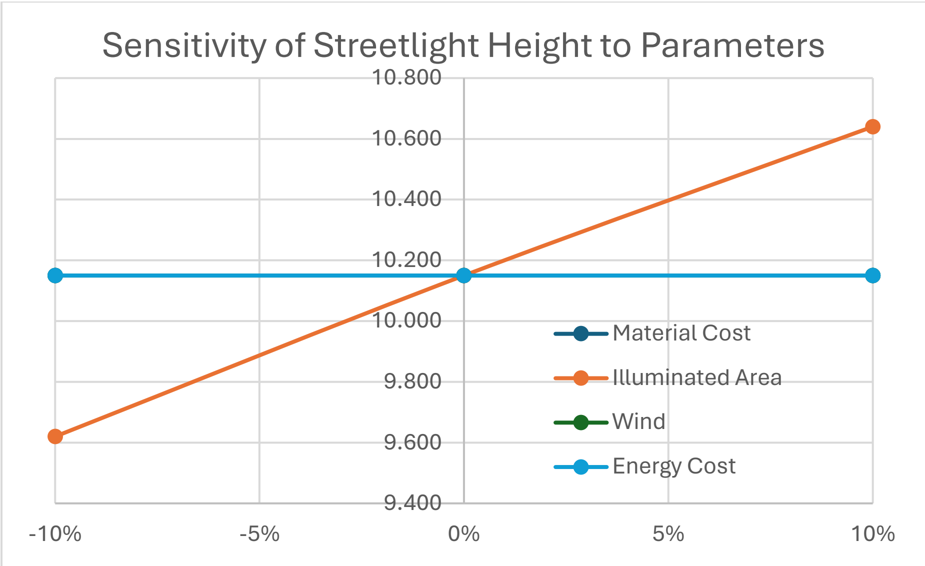


Fig 11. Sensitivity of Optimum Streetlight Height to Parameters

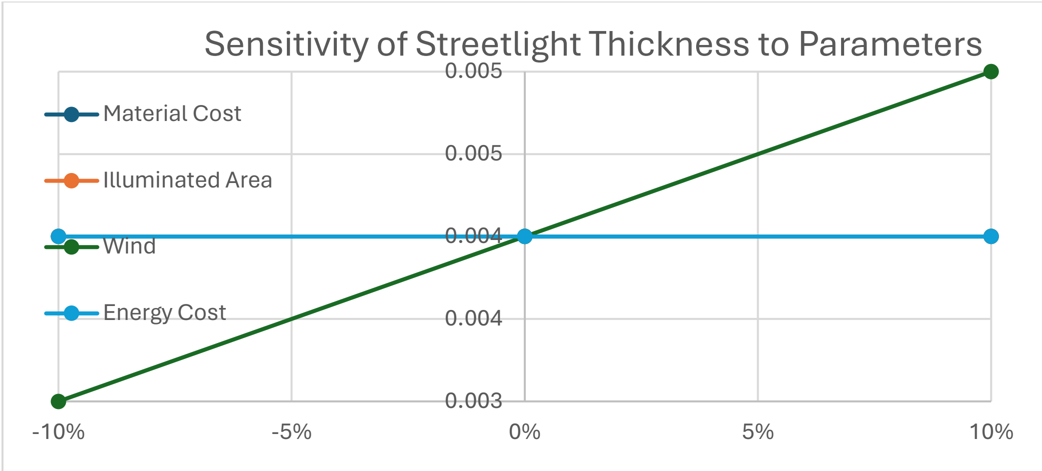


Fig 12. Sensitivity of Optimum Thickness to Parameters

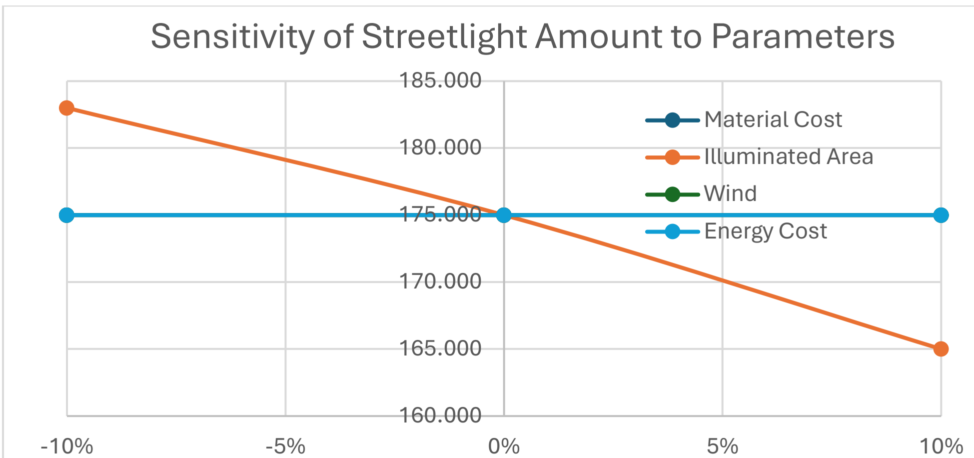


Fig 13. Sensitivity of Optimum Streetlight Amount to Parameters

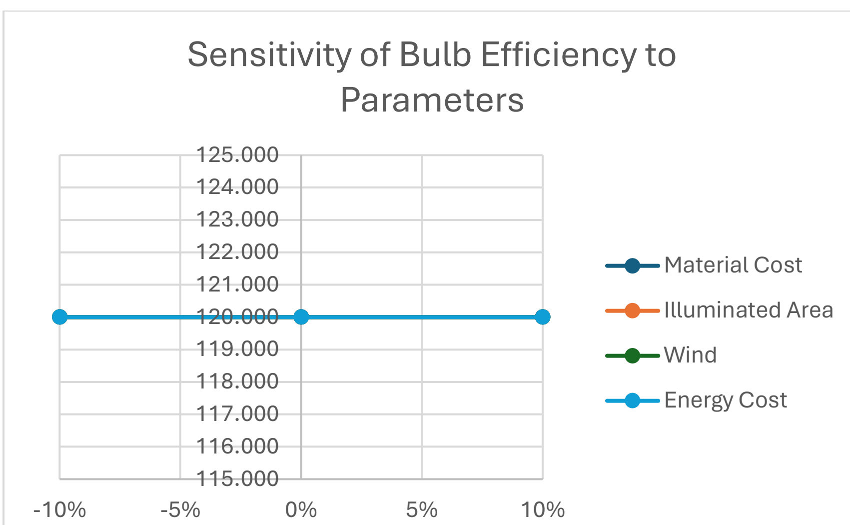


Fig. 14. Sensitivity of Optimum Bulb Efficiency to Parameters

The sensitivity analysis yields very relevant results. First, our NVF is most sensitive to varying energy costs. This is something that is of concern to us as energy rates are not fixed and can vary greatly from year to year [2]. This suggests that it is imperative that we remain up to date with the current energy market to ensure that our selected energy cost value actually represents the current costs. Further, our decision variables are hardly sensitive to the four parameters. For instance, the streetlight amount is only impacted by the illuminated area and not the 3 others. This can actually be seen as a good thing as it suggests that our optimum values have less variability regardless of outside factors. It is also worth noting that if a parameter is not visible on a graph it means it does not impact the variable and follows a horizontal line.

All in all, the sensitivity analysis has provided us with justification to be confident in our optimum values. The only point of major attention is the variance of energy rates along the course of our design implementation.

7. Final Design

The proposed solution we have discussed in this report by using wind turbine integrated streetlights is a way to reduce the cost of streetlights by promoting clean/regenerative energy use, while also reducing the dangers of driving in poor lighting conditions. Through economic analysis we were able to develop a net-value function of the project that over a 10-year period would create a positive value of over 2 million dollars. We have considered a variety of constraints, costs, and benefits to evaluate the project by considering all shareholders such as the general public, commuters, government and taxpayers. Most of the costs and constraints came from construction limitations, construction cost, material cost, electrical cost, design cost and project implementation costs, while the benefits included excess energy production, increased safety, and green energy promotion. Through sensitivity analysis and optimization, we considered the effects of changing streetlight heights, frequency, bulb efficiency, pole thickness, accident reduction and generator efficiency to allow us to maximize the value of the project. Certain variables such as streetlight height and frequency were more sensitive to change and could drastically increase the cost if altered.

Through the process of optimization, we concluded that the variables calculated in our technical analysis were ideal as they either provided the maximum benefit or minimum cost to our NVF, resulting in no change of our final design. With this in mind, it is important to consider the legitimacy of the costs/benefits we came up with. Ultimately, a project of this size could have many more unforeseen costs and require a lot more materials, labour, infrastructure, design, maintenance, and other factors that we have not been able to account for in the scope of this class. Further site research is also necessary to consider current electrical infrastructure and physical space available if the project design were to continue. In conclusion, the client should expect less of a return on the project due to these unknown variables.

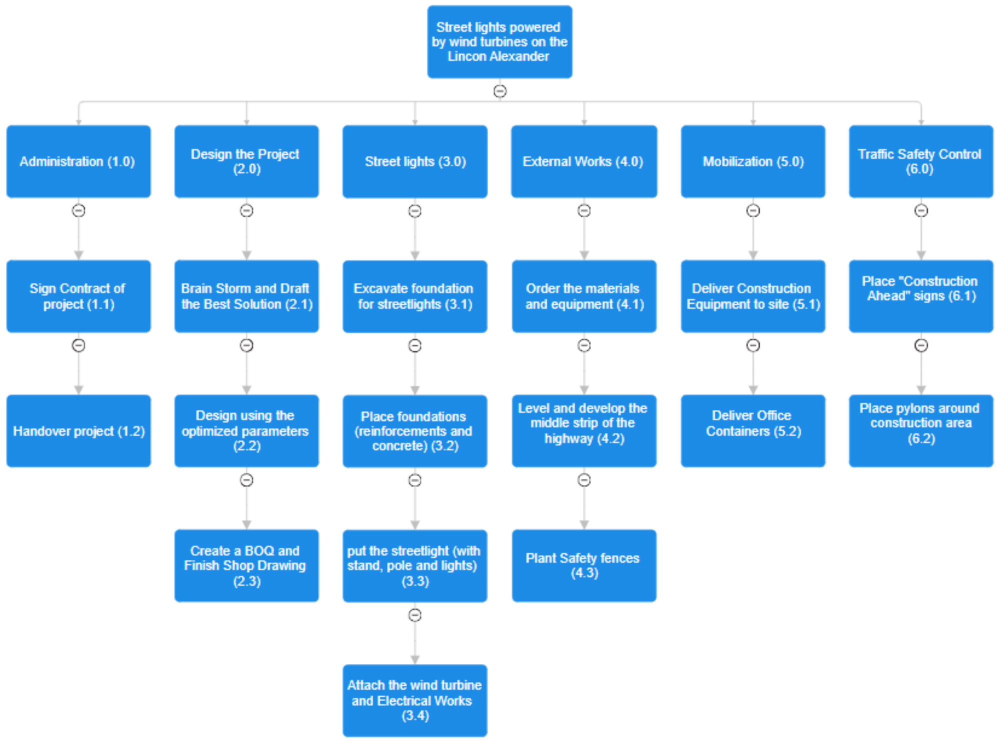
8. Project Plan

Task ID	Task Description	Start Date	End Date	Duration	Number Of Payments (all upfront payments)	NV Impact
1.1	Sign Contract of project	April 1	April 1	0 days	1	Included in current NVF (under adminstrative costs
1.2	Handover project	September 15	September 15	0 days	1	Included in current NVF (under adminstrative costs
2.1	Brain Storm and Draft the Best Solution	April 3	April 10	1 week	1	Included in current NVF (under design)
2.2	Design using the optimized parameters	April 10	April 17	1 week	1	Included in current NVF (under design)
2.3	Create a BOQ and Finish Shop Drawing	April 17	May 1	2 weeks	1	Included in current NVF (under design)
3.1	Excavate foundation for streetlights	May 22	June 1	1 week and 3 days	1	Included in current NVF (under installation costs)
3.2	Place foundations (reinforcements and concrete)	June 1	June 24	3 weeks and 2 days	1	Included in current NVF (under installation costs)
3.3	Assemble the streetlight (with stand, pole and lights)	June 24	August 3	5 weeks and 5 days	1	Included in current NVF (under installation costs)
3.4	Attach the wind turbine and Electrical Works	August 3	September 15	6 weeks and 1 day	1	Included in current NVF (under installation costs)
4.1	Order the materials and equipment	May 2	May 4	2 days	1	Included in current NVF (under construction and electrical materials)
4.2	Level and develop the middle strip of the highway	May 9	May 21	1 week and 5 days	1	Included in current NVF (under installation costs)
4.3	Plant Safety fences	May 21	May 21	0 days	1	Included in current NVF
5.1	Deliver Construction Equipment to site	May 5	May 7	2 days	1	Included in current NVF (under construction and electrical materials)
5.2	Deliver Office Containers	May 1	May 3	2 days	1	Included in current NVF (under construction and electrical materials)

6.1	Place "Construction Ahead" signs	May 3	May 4	1 day	1	Included in current NVF (under traffic closure costs)
6.2	Place pylons around construction area	May 4	May 5	1 day	1	Included in current NVF (under traffic closure costs)

Fig. 15. Task List for the duration of the project as well as the NV impact

After coming up with the final solution to the proposed problem, a list of tasks was created to bring the project to the real-world market. To begin, the project will start by signing a contract with the government which will give us the authority to work on the project under certain conditions, as well as handover period which closes the signed contract. The project initially consists of a brainstorming and designing phase where a group of civil, electrical and mechanical engineers get together to formulate the best solution, followed by optimizing such parameters, and then creating a shop drawing for construction. When creating a shop drawing for the project a detailed BOQ will be formulated by estimators to find the total price and quantities of materials. Which leads to ordering the materials/equipment, mobilizing and the overall construction phase. The finalized task list is in chronological order by section numbers, but the start/end dates suit a real-world scenario, for example, the project needs materials before even beginning construction hence why it will be ordered before the construction date and vice versa. The payments done will all be upfront since there all very low figures and the project is conducted with the city of Hamilton, a trustable client. There will be no impacts on the NV since the tasks were already included in our past NVF.



.

Fig. 16. WBS for the listed tasks in the project

A WBS was formulated to split up the different tasks and their appropriate sections, as stated in the task list. The WBS branches off into 6 different sections which are essential to the project's success, such as the administration (1.0) which indicates anything administrative such as signing contracts, designing the project (2.0), constructing/assembling the streetlights (3.0), any external works that include ordering materials and developing the land (4.0), Mobilization (5.0), traffic control (6.0). After the administrative and designing sections, the construction of the streetlights first starts in the "levelling and development of the middle strip on the highway" (4.2), which will help prepare the "streetlights" (3.0) section. The construction of the streetlights starts by excavating the levelled land, and then placing the foundations which includes steel rebars and concrete, leading to assembling the streetlights on the concrete foundation as well as attaching the wind turbine while finishing the electrical works. The other sections of the WBS include other important aspects of the project such as traffic control, safety, and mobilization.

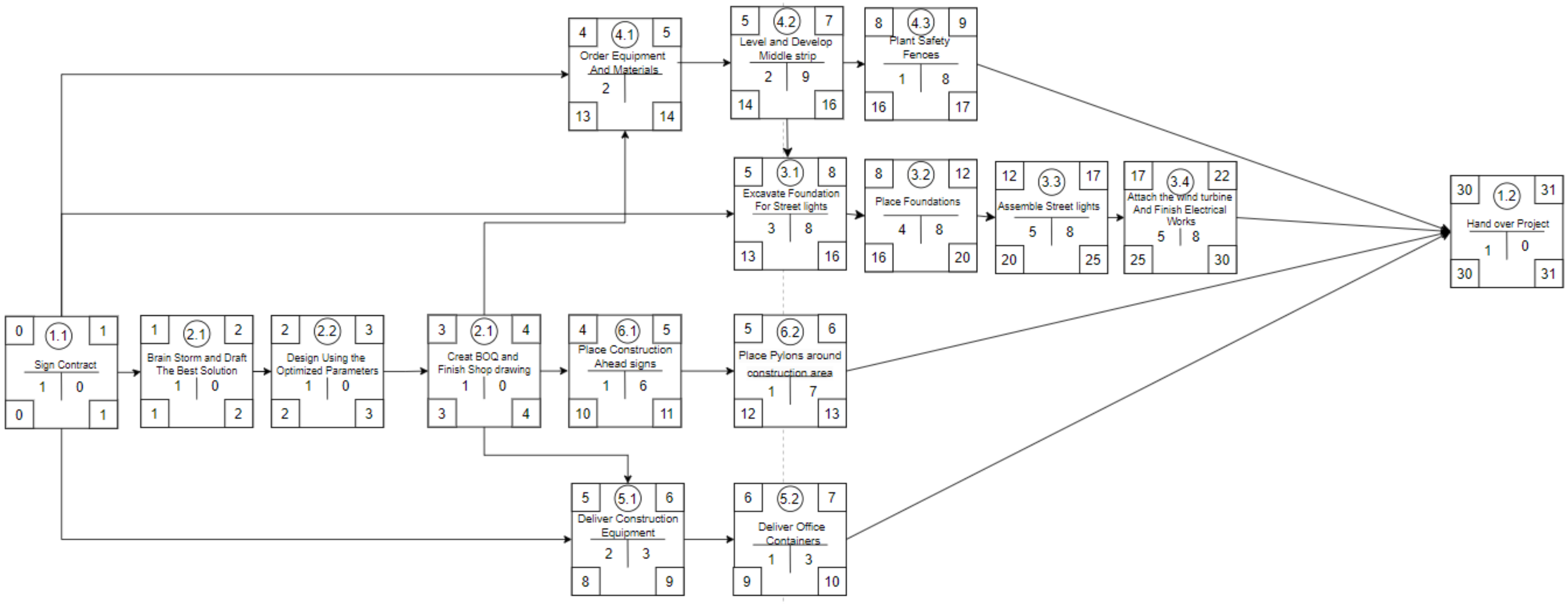


Fig. 17. CPM that underlines the different tasks in a node diagram

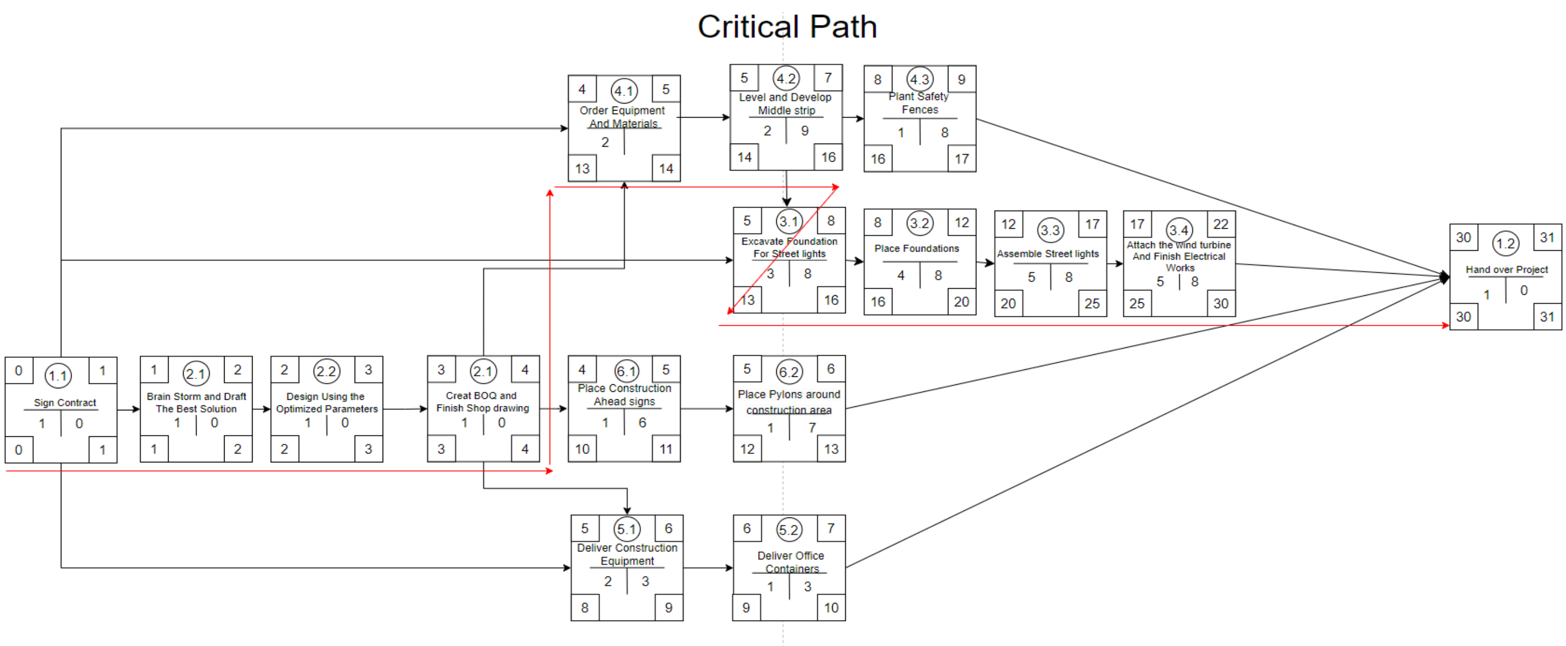


Fig. 18. CPM with the appropriate critical path

To conclude, a CPM was formulated to find the detailed phases of the project in a node diagram. The node diagram includes the section number of the task, the early start/end dates, late start/end dates, the duration of the task, and the float (the duration of delay until a successor task is affected). Nonetheless, the node diagram starts from the signing of the contract to the handover of the project, before any construction related task start, all the designing tasks had to be completed as a logical condition. After the BOQ is formulated the mobilization, ordering and construction begins. The duration of the projects as well as the early and late dates were calculated based on the task list, as each task can take on a minimum of a week. After following this node structure, it can be easily used as a tool to track progress in the project and any potential delays. After further analyzation, there will be a slight difference in the overall NVF in terms of material costs as there was not a detailed study of the overall costs in the project, items like concrete, rebar, pylons, safety signs, equipment rental etc. Such changes do not bring any new decision variables, but they slightly add to the overall fixed cost of construction. A critical path was identified in the total CPM starting from signing the contract to the designing and created a bill of quantities, then ordering materials, leading to levelling the strip, then the construction works of the streetlights ending off at the handover of the project.

9. NPV

Value Flow Diagram with Value Impacts from Project Plan Above:

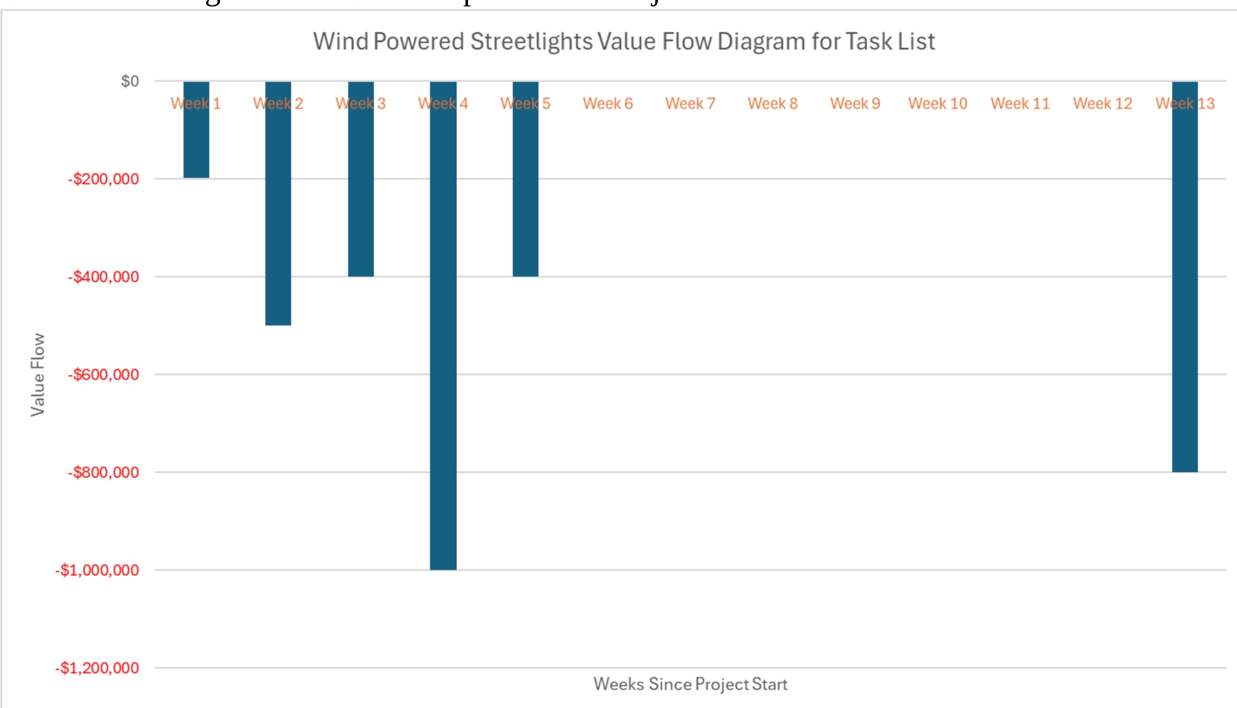


Fig. 17. Value Flow Diagram

As seen above, the tasks outlined in the task list all have a negative value, which contributes to the first roughly three months of our project having a negative value flow.

The discount rate selected for our project is 15%, this is because our project is relatively long-lasting, with a minimum 10-year span before major revision is needed. However, this is a long period and thus there is a high amount of uncertainty attributed to it. This means that our solution may be rendered obsolete by the end of this time frame due to emerging technologies or more pressing problems in the world. This requires us to attribute a larger penalty to our future cash flows to help ensure our calculations are realistic and conscious of unexpected future outcomes. Additionally, factors such as natural disasters and vehicle collisions resulting in damages to our project are an important consideration to make in terms of cost.

Our selected reference year is the present year, and the project is being analyzed over the next 10 years, in the table below we can see the TVM conversion factors for each year with our 15% discount rate.

Table 1. TVM factor by year.

Year	TVM Conversion w/ 15% Discount Rate
1	0.869565217
2	0.756143667
3	0.657516232
4	0.571753246
5	0.497176735
6	0.432327596
7	0.37593704
8	0.326901774
9	0.284262412
10	0.247184706

Given our selected reference year being the present (zeroth) year, we see that the costs outlined in our task list will be unconverted as they are costs, we are dealing with now. A reference calculation is included for the estimated revenue in four years using the TVM factors.

Table 2. NPV Values for tasks in task list as well as sample of TVM factor impacting future revenue.

Task	Date	Year	TVM Factor	NPV
Set up Construction Zone	5-1-2024	0	1	-$5,000
Order Materials	5-2-2024	0	1	-$191,800
Level and Develop Zone	5-9-2024	0	1	-$107,000
Install Safety Fences	5-21-2024	0	1	-$40,000
Excavate Foundation for Streetlights	5-22-2024	0	1	-$100,000
Foundation Reinforcement	6-1-2024	0	1	-$4,000
Install Streetlights	8-3-2024	0	1	-$80,000
Sample: Revenue TVM 4 Year Projection	6-15-2028	4	0.571753246	$156,089

The NPV considers all working decision variables included in the analysis performed in the optimization, of which there are no newly added decision variables. The project is projected to have a $527,000 startup construction and setup cost, after which the project has an expected $273,000 revenue per year. Using Excel, our project's NPV is determined to be $844,306. This is promising as it indicates that our returns are exceeding our costs that are largely at the beginning of the project.

The IRR for our project was determined to be 51% over the 10 years we are analyzing our project. This lets us know that our 15% discount rate will yield a positive NPV. This is also promising as it is indicative of a high potential for profitability and quick repayment of the initial capital required and is expected to have returns that will exceed the costs.

What if there was a 15% MARR?

This project should be pursued if the Minimum Acceptable Rate of Return was 15%, given that the IRR was determined to be 51%. Assessing the MARR with the IRR shows us that the IRR is not only greater than the MARR but substantially greater. This indicates that the project will likely be lucrative and a viable investment opportunity. Using this analysis, we would recommend the project at this MARR, but a more informed decision also considered factors such as risk should be considered before investing. This will be covered in the next section concerning risk management.

10. Risk Management

Considering possible risks that may occur during the construction or lifetime of our project is important because certain factors may largely influence our Net-Value Function. Many risks such as natural disasters, changes in price and changes in demand are difficult to predict yet can cause issues if not accounted for in the construction of a project like our proposed streetlight implementation. To organize potential risks that may occur, below is a risk matrix of possible instances that may affect our NVF. The 3 identified risks that will have the highest impact on our Net-Value are higher material costs for construction and/or electrical equipment, a large decrease in electrical cost (would lower the value of energy produced), and labour cost increase which would increase the installation/maintenance cost of the project.

		NV Impact Each Time it Happens			
		<$1000	$10,00-$50,000	$50,000-$15,0000	>$150,000
Expected Period of Happening	Once			-Design Cost Increases	-Material Cost Increases
	20 years			-Seismic damage	
	5 years	-Vandalism damages	-Crash causes streetlight to fall	-Energy Cost Decreases	
	1 year		-Installation/ Maintenance Cost Increases		
	1 month	-Poor weather lowers power output			

Fig. 18. Risk Matrix of Possible Risks

Of the 3 most impacting risks, we are able to alter the Net-Value Function to reflect these impacts. A material cost increase would affect the initial upstart cost of the project. Prices of concrete, copper, and wind turbines were determined to alter by a variable rate of about 20%. Although energy prices tend to increase over time, with the current promotion of clean energy and the increasing dependence on electricity, technology is becoming more advanced which may result in more efficient energy generation. We have prepared for a possible decrease in energy cost of about 10% which would lower the value of our energy generated, and therefore lower the profit generated by the project. Lastly, the installation and maintenance cost effected by labour rates and equipment costs can increase by around 20%. These risks can be shown in our NVF by using a stochastic model. The stochastic model uses a random input in the desired range of probability these changes would occur and allow us to generate a more accurate NVF shown in figure 19 below.

Parameter Name	**Value**		
# of light poles (#)	175	Original NVF (negatives)	-527800
Construction Material Cost ($)	406	Original NVF (positives)	2733950
Electrical Material Cost ($)	690	NVF TOTAL	2206150
Installation Cost ($)	1720		
Traffic Closure Cost ($)	5000		
Design Cost ($)	25000		
Administrative Cost ($)	5000		
Value Benefit of Road Conditions ($)	365000		
Value of Energy Generated ($)	2529450		
Value of Energy Used ($)	220500		
Cost Benefit of Clean Energy Promotion ($)	60000		
Input Random Variable	**Value**	New NVF (Negatives)	-624345
Material Cost Increase (Construction & Electrical)	33.02%	New NVF (Positives)	2166180
Energy Cost Decrease	11.04%	New NVF TOTAL	1541835
Installation/Maintenance Cost Increase	24.59%		

Fig. 19. Stochastic Model Net Value Change

The updated value of our project has reduced from $2,206,150 to $1,541,835. Although that is a large sum, it is important to consider that there are ways to mitigate these risks. In order to reduce the chance of a material cost increase the project should commence as soon as possible, as shown in the task list. Purchasing materials as soon as possible will reduce the chance of price change and allow our initial NVF to be more accurate. To reduce the effects of energy cost decreases, we can alter the design of the streetlight to allow easily interchangeable wind turbines. New more efficient turbines and generators may be developed in the future which would allow more energy to be produced and increase our energy generated profits to hedge against a lower energy cost. Similar to the material cost, the sooner the project commences, the lesser chance of wage increases or equipment rate costs. This would mitigate the increase in installation and maintenance costs that are expected to occur in the future.

11. Stochastic Sensitivity Analysis

When performing stochastic sensitivity analysis on the final version of our NVF, we made several considerations and conversions. This final NVF includes elements from project planning, considerations from the time value of money and risk management sections.

Final NVF:

NV = - [# of light poles(construction materials (discrete variable with three probabilities) + electrical materials)] - [# of light poles*(installation costs) + traffic closure cost] - [Design + Administrative Costs]*

+ [Value Benefit of Road Conditions] + [Value of Energy Generated (continuous, normally distributed variable)– Energy Used] + [Cost Benefit of Clean Energy Promotion] + [Maintenance costs (Discrete variable with two possibilities)

Previous NVF Total: $2,206,150

New NVF Total: $2,185,745

Our stochastic sensitivity analysis made considerations for three major components of our design. First, the material cost which could be subject to price changes and is modeled as a discrete variable. We attributed three different probabilities to this; that the material is on sale, regularly priced or experiencing increased price. Each possibility has probabilities of 30%, 60% and 10% for each possible change respectively. Next, for energy cost, we decided for it to be a normally distributed continuous variable with a mean of 0.11 to the variable which has a value of $0.12 typically. Finally, for maintenance cost, we modeled it again, as a discrete variable with a 20% chance of damage in a 10-year period and an 80% chance of no damage occurring. For each of these, both for material cost and maintenance, we attribute a cost to each probability as can be seen in the table below.

Input Random Variable	**Value**	**Explanation**
Material Cost Increase (Construction & Electrical)	1096	Discrete variable: 30% chance on sale --> $850 60% chance regular --> $1096 10% chance overpriced -> $1300
Energy Cost ($/kWh)	0.11	Normally Distributed Continuous Variable with mean 0.11
Maintenance Cost	850	Discrete variable: 20% chance damage in 10y --> $850 80% chance no damage --> $0

Then, we converted our stochastic model into a deterministic model in two main ways depending on whether our variables were discrete or not. For discrete variables, they were converted using the expected value equation for discrete variables (EV = sigma($probability_i$*$value_i$)). For our continuous random variable, we used its mean to convert it as it is normally distributed.

By optimizing our deterministic model, we obtained that our previous calculations were largely accurate, we noticed little to no change as compared to our original optimization. Because of this, we see that our previous calculations and optimizations were in close alignment to the results obtained after we optimized our deterministic model. This is additionally evident when comparing our original NVF to our final NVF, with there being a very minor difference.

After optimizing the deterministic model, we returned to the stochastic model to obtain the final NPV and perform a sensitivity analysis. This was done by converting cash values (including the random variables) to their net present value. A Monte-Carlo simulation was then run with 2000 iterations to simulate an entire population of data. The corresponding mean and standard deviation of our NPV was calculated to be $713,939.9 and $21505. This indicates that our project is very likely to be worthwhile is has a near zero probability of not having a positive NPV. Specifically, the probability of yielding a negative NPV is close to 10^{-200}, essentially 0.

Thus, it is certainly favourable for us to continue with this project given the high probability of success.

12. Final Recommendations

Through the duration of the project, numerous skills and techniques were used to analyze the economic impacts of our proposed project. Devising a project plan was a way to break down the project from start to finish which allowed us to determine the critical path. Setting the project up in order from beginning to completion allowed us to thoroughly examine the NVF and research more in depth on all the decision variables. Using NPV analysis and comparing the IRR to MARR we were able to determine how the initial costs of the project would impact our net value and compare them to the total return, proving to be a positive investment. Using risk management techniques, the net value function was altered to account for possible changes between the time of design and time of completion of project/project lifetime. Although lowering the expected return, using the risk management techniques provided a more accurate project valuation. Stochastic sensitivity analysis was done to finalize the expected NPV for our stochastic model and predict the likelihood that the project would produce a positive value.

The difference between the simple report initial NVF from the simple report and the finalized NVF is that the simple report was a best-case scenario, generalized approach to the project. The simple report didn’t include any unforeseen variables such as risks or time factors that the final NVF would consider through the techniques of stochastic/deterministic modelling and NPV calculations. From an engineering standpoint, the economic viability of our project may not be accurate enough to proceed with the project. While our calculations on produced energy is significant, and research based, There are many assumptions made to analyze our proposed solution, such as existing technology already in place along the Linc, generalized installation costs, and geotechnical concerns along the highway. These assumptions are made for the sake of this report, and if the project were to continue, further onsite research is recommended.

Appendix:

References:

[1] “2018 Annual Collision Report City of Hamilton Appendix ‘A’ to Report PW19104.” Available: https://pub-hamilton.escribemeetings.com/filestream.ashx?DocumentId=211535

[2] “Home Energy Costs in Ontario,” Financial Accountability Office of Ontario (FAO), https://www.fao-on.org/en/Blog/Publications/home_energy (accessed Mar. 15, 2024).

Assuming use of a Synchronous Generator:

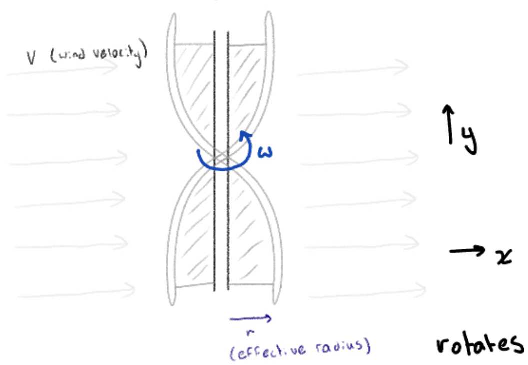
high level equation:

$$P_{out} = K \times \Phi \times N \times \omega \times \eta$$

- P_{out}: 'Power out'
- K: generator constant parameter
- Φ: Flux in copper windings of generator
- N: Number of copper windings in generator
- ω: Angular turbine Velocity
- η: generator efficiency

How can we convert wind speed to 'ω' turbine velocity?

For the scope of this technical analysis: we will use a simplification that converts wind velocity to angular rotational speed $\omega = \frac{V}{R}$



$\omega = \frac{V}{r}$

rotates about light pole in 'y'

$$P_{out} = K \times \Phi \times N \times \omega \times \eta$$

$$P_{out} = K \times \Phi \times N \times \frac{V}{r} \times \eta$$

Finally, we convert Power Output to a monetary value:

$\$_{generated} = \$/watt \cdot P_{out}$

$\$ \text{ of energy generated} = \$/watt \times K \times \Phi \times N \times \omega \times \eta$

Mechanical Technical Analysis (Mechanical → Electrical Conversion):

$K \rightarrow$ wind turbine constant $\rightarrow K = \frac{1}{2}\rho A$

$= \frac{1}{2}$

$A = 8ft^2 = 0.7432m^2$

Assuming $8ft^2$ effective area of the $1.225\ kg/m^3$

$$K = \frac{1}{2}(1.225\ kg/m^3)(0.7432\ m^2)$$

$$K \cong 0.45521$$

Avg Hamilton wind speed:

$4.77\ m/s \cdot 1.2$ (amplification for roadside vehicle speed)

$$\frac{v}{r} = \omega = \frac{4.77 \cdot 1.2}{2} = 2.865$$

$$\omega = 2.865$$

1500 W power output required:

$P_{out} = 1500$ watts

$K = 0.45521$

$\omega = 2.865$ rad/s

$\eta = 0.65 \longrightarrow$ efficiency assumed to be significantly below unity.

$A = 0.743224\ m^2$

To figure out $\Phi \times N$, we use $\Phi \times N = \frac{P_{out}}{K\omega\eta}$

$$\Phi \times N = \frac{1500}{0.45521 \times 2.865 \times 0.65}$$

$$\Phi \times N = \frac{1500}{0.786745}$$

$$\Phi \times N = 1009.617$$

$$\Phi = B \times \text{Effective area}$$

looking at internal assumed armature geometry;

we assume effective area to be $4ft^2$

$= 0.37161\ m^2$

B → magnetic field strength $\cong 0.5$

$$\Phi = 0.37161 \cdot 0.5$$
$$= 0.1858$$

Now, calculating 'N' windings for the system

$$N = \frac{1009.617}{0.1858}$$

$$N = 5433.745$$

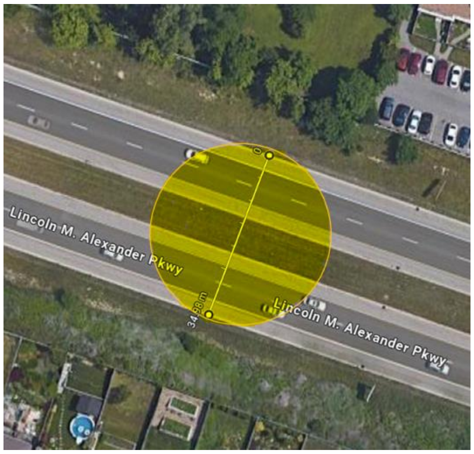
ROUND TO 5500 copper windings

to yield $\approx$ 1500 watts or 1.5 Kw of power.

ontario electricity rates $\cong 1.5\,\text{Kw} \cdot \frac{11\,¢}{\text{Kwh}} \cong \boxed{16.5\,¢/\text{hr}}$

Fig. 9. Mechanical Engineering Technical Analysis Electricity Generation

Civil Engineering – Transportation Optics



Assuming the streetlight acts as a point source of light, the following formula can be used to determine its expected illuminance.

$$E = \frac{I}{4\pi r^2}$$

E = illuminance, I = luminous flux, r = distance from point source (light height)

The formula below can be used to determine the expected illuminated area from the light source, due to its illuminance, luminous flux, and the light height.

$$A = \frac{L}{E} - \pi r^2$$

A = illuminated area, L = Luminous flux, E = illuminance, r = light height

$$E = \frac{40000}{4\pi r^2} = \frac{10000}{\pi r^2}$$

$$A = 970m^2 = \frac{40000}{\frac{10000}{\pi r^2}} - \pi r^2 = 4\pi r^2 - \pi r^2$$

$970 = 3\pi r^2$, rearrange for r, $r = \sqrt{\frac{970}{3\pi}} \cong 10.15m$

Fig. 10. Civil Engineering Technical Analysis Transportation Optics/Optimal Streetlight Height

Civil Engineering Technical Analysis:

Alex Di Francesco: Pole thickness, Cost of steel.

Technical Analysis for the optimal thickness of Steel in the light pole. Thickness can be altered depending on height of the pole, and wind speeds. Many assumptions were made such as a max wind speed of 40 m/s, air density of 1.3 kg/m^3, and an allowable deflection of L/360.

$$\Delta x\ allowable = \frac{h}{360} = \frac{10.15}{360} = 0.0282$$

$$Wind\ Load = \frac{1}{2}p * v^2 * A$$

$$\sigma = \frac{1}{2} * (1.3) * 40 = 1040 N/m^2$$

$$A = \frac{b+a}{2} * h = \frac{0.6+0.2}{2} * 10.15 = 4.06 m^2$$

$$w = \frac{\sigma}{h} = \frac{1040 * 4.06}{10.15} = 416\ N/m$$

$$\delta = \frac{wh^4}{8EI} = \frac{416 * 10.15^4}{8(200 * 10^9)I} = 0.0282$$

$$I = 9.78 * 10^{-5}\ m^4$$

$$I = \frac{\pi(d1^4 - d2^4)}{64} = \frac{\pi\left(d1^4 - \left(d1 - (2 * t)\right)^4\right)}{64} = 9.78 * 10^{-5}\ m^4$$

$$if\ d1 = 0.4m\ avg, t = 0.004m$$

It was determined that for a 10.15 m tall light pole, the optimal thickness of steel is 4 mm.

Average Cross sectional Area:

$$A = \frac{\pi(d1 - d2)^2}{4} = \frac{\pi(0.4^2 - ((0.4 - 2 * 0.004)^2))}{4} = 0.00498 m^2$$

Cost of steel:

Steel is 7850 kg/m^3
Assume $1/kg

Cost per m:

$$\frac{7850kg}{m^3} * \frac{\$1}{kg} * 0.00498 = \$40/m$$

Fig. 11. Civil Engineering Technical Analysis Pole Thickness/Cost of steel